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THE EFFECT OF ABRASIVE BLASTING ON THE FATIGUE AND CORROSION OF AN ALUMINIUM-COPPER ALLOY

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SUMMARY

Rotating bending fatigue tests have established that glass bead and alumina grit blasting have only a slight effect on the fatigue properties of 2014-T6 aluminium alloy. Exposure to salt fog for 8 hours or alternate immersion in 3½% salt solution for 3 days reduces the fatigue strength from 170 MPa to 107 MPa and 64 MPa respectively but substantial improvements in fatigue strehgth may be achieved by abrasive blast cleaning to remove the corrosion.

Total immersion tests made in 3½% salt solution to examine the effects of abrasive blasting on corrosion have demonstrated that the corrosion rate and type of pitting attack on 2014-T6 aluminium alloy sheet are dependent on the abrasive used and on the amount of corrosion which has occurred prior to blast cleaning.

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1 INTRODUCTION

Impact blasting techniques such as shot peening and abrasive blast cleaning are widely used in the aerospace industry for the preparation of metal surfaces. In shot peening operations, the workpiece is blasted with a high velocity stream of spherical particles such as glass balls or steel shot in order to induce compressive stresses into the surface. The process is mainly used to improve the fatigue strength of components and to give improved resistance to stress corrosion cracking. Abrasive blast cleaning is used to remove corrosion products or scale from metal components or to roughen the surface in preparation for bonding, painting or metal coating. The abrasives which are employed include alumina grit, angular metallic particles, crushed slag and smooth glass beads.

In recent years abrasive blast cleaning with either small diameter glass beads or fine alumina grit has been used to blend out corrosion damage on aircraft. One area where it has proved to be invaluable has been in the repair of corrosion damage which sometimes occurs adjacent to countersink fasteners, particularly on upper wing skins. Prior to the introduction of abrasive blast cleaning, the corrosion was blended out by hand using metal wool, abrasive pads or small abrasive wheels mounted in a power drill. This could take up to 2 hours for a single fastener head but by using abrasive blasting techniques this time has been reduced to a few minutes.

When abrasive blast cleaning methods were first introduced for use on military aircraft glass beads were preferred to alumina grit because they readily remove brittle corrosion products but remove little of the ductile metal substrate. It became apparent, however, that although the surface appeared free of corrosion after blasting the peening action of the glass beads could deform the surface layers and cause small pockets of corrosion in pits or intergranular sites to become trapped. There was concern that these pockets of buried corrosion might act as stress concentrators which could accelerate fatigue crack initiation or allow enhanced corrosion attack. A change to alumina grit blasting was therefore made in order to ensure that all the corrosion was blended out even though this would lead to a significant amount of metal removal.

The aim of the present work has been to quantify the effects of abrasive blast cleaning on the fatigue and corrosion of a 2014-T6 aluminium alloy which is used extensively in airframe construction in the UK.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

The 2014-T6 aluminium-copper alloy chosen for this investigation was available as both sheet and plate material. 8mm thick plate to BS L93 was used for the fatigue evaluation programme and 1 mm sheet to BS L150 was employed for the corrosion studies.

2.2 Abrasive blast cleaning

Abrasive blasting was carried out using a Junior VP machine which is manufactured by Vacu Blast Ltd and is similar to equipment currently in service with the Royal Air Force. The blasting pressure was maintained at 550 kPa and the distance between the gun nozzle and the workpiece at about 40 mm, values representative of those used in service. Both

180-220 mesh alumina grit and 75-150 μm glass beads were used in this programme and blasting was carried out until complete coverage was achieved. Test coupons used in the corrosion evaluation were hand held, but cylindrical specimens, used to study the effects of abrasive blast cleaning on fatigue, were mounted in a small jig which allowed them to be rotated during the blasting operation.

2.3 Fatigue testing

Fatigue specimens to the design in Fig 1 were machined from the 8mm thick L93 plate with the specimen axis parallel to the rolling direction. One set of specimens was corroded for 8 hours in 5% neutral salt fog (BS 5466, part 1) and a second set was corroded for 3 days by alternate immersion in 3½% salt solution (ASTM G44). A selection of the as-machined and corroded specimens were abrasive blast cleaned using either glass beads or alumina grit prior to fatigue testing.

Fatigue tests were made to establish the effects of corrosion, of abrasive blasting, and of corrosion followed by abrasive blasting on the fatigue strength of L93 alloy. All fatigue testing was carried out on a rotating bending machine operated at a frequency of 100 ± 5 Hz. Tests were continued for at least 5×10^7 cycles unless failure occurred earlier.

2.4 Corrosion tests

Weight loss experiments were made on small coupons approximately 40 mm × 25 mm cut from the L150 sheet and drilled with a 2 mm diameter hole approximately 5 mm from the centre of one of the short sides. Coupons were then either wet abraded on grade 1000 silicon carbide paper, or abrasive blasted with glass beads or alumina grit. After washing with acetone, the coupons were dried and weighed to the nearest 0.1 mg. Each coupon was suspended by a glass S hook so that it was completely immersed in 90 ml of 3½% NaCl contained in a polythene beaker. To reduce evaporation losses, the beakers were placed in a water bath covered by a transparent hood. The temperature of the water bath was held at 25 ± 0.5°C throughout the 3 week test period. Coupons were removed after various immersion times, washed in running water and freed from corrosion product by immersion in a gently boiling aqueous solution containing 7.5 g/l chromium trioxide and 5 ml/l phosphoric acid for 20 minutes. After rinsing in water and acetone, the coupons were dried and reweighed.

A second series of immersion tests was made on material which had been corroded before abrasive blast cleaning. Sets of coupons were prepared by wet abrading and then immersing in 3½% salt solution for either 1, 4, 7 or 12 days. The corrosion on the coupons was then removed by either alumina grit or glass bead blasting. After weighing coupons were re-immersed in 3½% salt solution for various times, cleaned in chromic-phosphoric acid solution and reweighed. Selected weight loss coupons were examined using optical metallography to determine the size and distribution of pits after corrosion.

3 RESULTS AND DISCUSSION

3.1 Effect of abrasive blast cleaning on fatigue

The fatigue data obtained for material in the as-machined condition are presented in Fig 2a in the form of an S-N curve (stress versus number of cycles). The curve has been used as the baseline against which the effects of abrasive blasting and corrosion on fatigue have been assessed.

Fig 2b&c show that at high stresses glass bead blasting gives some improvement in fatigue life but at lower stresses the data points for glass bead and alumina grid blasted specimens fall within the scatter band of the as-machined material. Estimates of the fatigue strength at 10^7 cycles are given in Table 1.

The results for alumina grit blasted material are in keeping with those reported by Myllymaki and McDonald[1] for a 7075-T6 aluminium alloy which showed that abrasive blasting with either fine alumina grit or coarser crushed slag grit had little effect on fatigue strength.

Very little data have been published on the effects of blasting with small diameter glass beads on the fatigue properties of aluminium alloys. S-N data obtained by Faulkner[2] demonstrated that glass bead blasting increased the fatigue strength of forged 2014-T6 aluminium alloy, BS L65, from 223 MPa to 254 MPa at 10^7 cycles. The glass beads used were 120 to 220 μm in diameter, slightly larger than those employed in the present study (75-150 μm) but considerably smaller than the ones generally used for shot peening purposes (600-800 μm).

The fatigue properties after abrasive blasting will be influenced by the surface roughness and the residual stresses at the surface of the component. Deep notches or pits tend to shorten the fatigue crack initiation stage whilst compressive stresses act to prevent the nucleation of fatigue crack and so extend the fatigue life. In the present work optical studies of sectioned and polished fatigue specimens show that the surface after glass bead blasting is free of notches whilst some small notches are visible on alumina grit blasted specimens, the largest of which are approximately 80 μm deep. Myllymaki and McDonald[1] suggest that any deleterious effect of notches produced by grit blasting may under some circumstances be offset by the beneficial effects of the compressive stresses introduced by the blasting operation. It seems unlikely that, in the present tests, residual compressive stresses will play a significant role in inhibiting the nucleation of fatigue cracks after alumina grit blasting: data presented by Birley *et al*[3] indicate that when the alumina particles are 65-85 μm diameter (equivalent to the 180-220 mesh size used in this investigation) the compressive surface stress is only 17 mPa and the depth of the compressive layer is less than 100 μm. It is concluded that the small notches present after alumina grit blasting, probably shallower than the compressive layer, are unlikely to give rise to early fatigue crack initiation.

The situation may be rather different after glass bead blasting where high compressive stresses may be present at the surface. Measurements made by Birley[4] on an aluminium-zinc-magnesium alloy have shown that abrasive blasting with small glass beads

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gives a surface compressive stress of 250 MPa. This is similar to the residual stresses measured by Köhler[5] and of the same magnitude as the stresses resulting from peening with coarse steel shot reported by Hawkes[6], Gaillard *et al*[7] and Was *et al*[8]. However the depth of the compressive layer, which according to Was *et al*[8] must be large to obtain maximum improvement in fatigue life, is dependent on the diameter of the glass beads used. Birley[4] has shown that with small diameter beads, similar to those used here, the depth of the compressive layers is probably less than 50 μm whilst other studies[6-8] have established that peening operations using 600 μm diameter shot can produce a compressive layer greater than 400 μm deep. The shallowness of the compressively stressed layer following abrasive blasting with small diameter glass beads suggests that the process will give only minor improvements in fatigue life, which is in line with the fatigue data in Fig 2c.

3.2 Effect of corrosion on fatigue

The fatigue curves in Fig 3a&b demonstrate the catastrophic effects which prior corrosion can have on the fatigue behaviour of L93 aluminium alloy. 8 hours exposure to neutral salt fog generates sufficient corrosion to reduce the fatigue strength from 170 MPa to 107 MPa. Small coupons of the alloy given the same corrosion treatment were found to have an average weight loss of 70 $\mu g/cm^2$ and an average pitting depth of 20 μm. Material which had been more severely corroded by alternate immersion in 3½% salt solution for 3 days exhibited a further reduction in fatigue strength as indicated in Table 1. In this case the weight loss was 1100 $\mu g/cm^2$ and the pitting depth 120 μm.

Several investigations have been made into the effects of corrosion on the fatigue of aluminium alloys. Weston and Wilson[9] for example carried out tension-tension fatigue tests on round bar specimens machined from 25 mm thick 7010-T7651 aluminium alloy and found that the fatigue strength was reduced by 70 MPa when specimens were pre-exposed to 8 hours 5% salt fog (ASTM Specification B117). In a study of the aluminium alloy 7075-T6, 't Hart *et al*[10] looked at the effects of corrosion on the fatigue life of tension-tension cylindrical specimens tested under constant amplitude loading. Corrosion was induced by alternate immersion in 3½% salt solution for various times up to 384 hours. After 48 hours exposure, the fatigue life was reduced from 1.9×10^6 cycles to 2.1×10^5 cycles. 't Hart *et al* observed that increasing exposure times produced further decreases in fatigue life but the drop was not proportional to the corrosion time. The fatigue life was found to be very dependent on the depth and density of pits, and metallography revealed that fatigue cracks nucleated at corrosion pits. Parson[11] has shown that for a number of aluminium alloys including unclad 2014-T6 sheet that the first 80 μm of pitting accounted for most of the loss in fatigue strength, deeper pitting led to further small reductions in fatigue strength.

The fatigue results, which have been obtained, follow the general trend which has been identified in the various studies described above. Small pits can drastically reduce the fatigue life and fatigue strength. As the pit size is increased further reductions in fatigue properties may occur but these will not necessarily be proportional to the depth of attack. At stresses near the fatigue strength, the initiation stage accounts for most of the fatigue life with the crack propagation stage probably occupying less than 20%.

If defects such as corrosion pits are present at the surface, they will act as stress raisers and assist in the initiation of fatigue cracks. When the pit depth is sufficiently large, the initiation stage will be almost eliminated and the fatigue life will be a fraction of the unpitted material. Further increases in the depth of pitting will therefore only yield relatively small reductions in fatigue life.

3.3 Recovery of fatigue properties by abrasive blast cleaning

Fatigue data for corroded specimens which were cleaned using either alumina grit blasting or glass bead blasting are reproduced in Fig 4 and show that substantial improvements in fatigue life can be achieved. Values of the fatigue strength are included in Table 1.

The percentage recovery in fatigue strength, R, may be calculated from the data in Table 1 using the following expression,

$$R = \frac{\sigma_A - \sigma_C}{\sigma_M - \sigma_C} \times 100 \quad (1)$$

where σ_M is the fatigue strength of the as-machined material, σ_C is the fatigue strength after a corrosion treatment, and σ_A is the fatigue strength after the corrosion products have been removed by abrasive blast cleaning.

A value of R = 0% indicates that there has been no improvement in fatigue strength whilst R = 100% implies that the fatigue strength of the as-machined material has been completely recovered.

The values of R calculated using equation (1) are listed in Table 2. For material which was exposed to 8 hours salt fog before testing a slightly greater percentage recovery in fatigue strength can be achieved by cleaning with glass beads (84%) rather than alumina grit (68%). Even with heavily pitted material, a 53% recovery in fatigue strength is possible using glass bead blasting.

The results discussed earlier suggest that any compressive stresses introduced into the surface as a result of alumina grit blasting will do little to inhibit the initiation of fatigue cracks. Instead the main action of the cleaning process is to blend out the corrosion pits to leave a shallow depression. When glass bead blasting is used, the rate of metal removal is much lower and the peening action of the beads will plastically deform and smooth out material at the base and sides of the pits rendering them less efficient as stress raisers.

3.4 Effect of abrasive blasting on corrosion

In the first series of experiments the effect of surface finish on the corrosion behaviour of L150 sheet was investigated. The weight loss data plotted as a function of the immersion time in Fig 5 show that the rate of corrosion is dependent on the type of surface treatment which was applied. After 21 days immersion the corrosion rate was estimated to be 5.6 mg dm^{-2} day^{-1} following wet abrading, 4.2 mg dm^{-2} day^{-1} after alumina grit blasting and 2.0 mg dm^{-2} day^{-1} for sheet which had been impact blasted with glass beads. An examination of the weight loss coupons using optical microscopy revealed that a few fairly large pits (>1 mm diameter) develop on the surface of the samples which have been glass bead blasted whilst on the wet abraded and alumina grit blasted specimens a large number of smaller pits form. These differences are clearly shown by the histograms in Fig 6 which give the distributions of pit diameters for the three surface conditions following 21 days immersion.

The second series of corrosion experiments undertaken were designed to investigate the effects of corrosion prior to abrasive blasting on the corrosion behaviour of L150 sheet. The weight loss data have been plotted as a function of the immersion time in 3½% salt solution in Figs 7 and 8.

Fig 7 refers to coupons which were alumina grit blast cleaned and shows that when the prior corrosion treatment is 1 to 7 days, there is very little if any increase in corrosion rate compared to L150 grit blasted before corrosion. Extending the prior corrosion treatment to 12 days gives a slight increase in the corrosion rate, but the rate is still less than that for wet abraded material. The situation is rather different with glass bead blast cleaned samples. Fig 8 shows that with prior corrosion treatment of 1 to 7 days there is a slight increase in corrosion rate, compared to L150 glass bead peened before corrosion, but with a 12 day prior corrosion treatment there is a large increase in corrosion rate. The sequence of optical micrographs reproduced in Fig 9 indicates that the pattern of corrosion observed in the preliminary experiments is repeated provided the prior corrosion treatment does not exceed 7 days. After 28 days immersion the surfaces of the coupons which were glass bead blast cleaned appear to be free of corrosion apart from a few large pits whilst large areas of pitting are seen on the alumina grit blasted samples. The histograms in Fig 10 comparing the distribution of pit diameters after corrosion emphasise the differences between the glass bead and alumina grit blasted material.

The increase in corrosion rate observed with glass bead blast cleaned material which was given a prior corrosion treatment of 12 days is associated with a change in the type of corrosion attack. The optical micrographs in Fig 9 show that after 23 days immersion in 3½% salt solution, the surfaces of both the alumina grit and glass bead blasted samples were covered with many small pits.

In the absence of a detailed electrochemical study only a tentative explanation of the effects of abrasive blasting on the corrosion of aluminium can be offered, based on current theories of pitting. An assessment of the processes leading to pit nucleation in iron and aluminium has recently been made by Janik-Czachor *et al*[12]. The authors have considered the growing evidence in favour of the involvement of flaws or weak spots, which are present in the oxide film, in the initiation of pits on aluminium. The flaws are thought to be associated with grain boundary triple points, precipitates and intermetallics in the metal substrate. Wood *et al*[13] had proposed earlier that pits initiate at flaws and propagate by metal dissolution into the substrate, thus undermining the oxide film. Changes in the surface structure will alter the number and type of flaws which form in the oxide film and consequently affect the pitting behaviour.

During alumina grit blasting, metal is removed from the surface and the level of compressive stresses introduced is small. The surface will be similar in structure to an abraded surface and the oxide film which forms will contain a similar density of flaws to the air formed oxide film on an abraded surface. When glass bead blasting is undertaken, the hammering action of the beads plastically deforms the surface metal and destroys the grain structure. The process tends to break up precipitates and intermetallics in the surface, and creates a thin highly stressed homogeneous layer. Fewer flaws will be present in the oxide film so that there will be a smaller number of sites available for pit nucleation.

The growth of corrosion pits is to a large extent controlled by the relative areas of the cathodic and anodic sites on the surface of the metal. A small anode area coupled to a large cathode area will lead to very intense localised attack and this is the situation which probably exists after glass bead blasting. The number of anodic sites or flaws is small but the cathode area is relatively large so that a few large pits will form.

The ability of the glass bead blasting process to eliminate the effects of prior corrosion on subsequent corrosion behaviour will clearly depend on the depth of the initial pitting attack. Small pits may be smoothed out by the blasting operation so that they do not give rise to flaws in the oxide film which forms on the surface, but this will not be the case with deeper pits. It is suggested that many of the pits which formed on material that was first corroded for 12 days and then glass bead blast cleaned were associated with pits present after the initial corrosion treatment.

The results presented in this section show that the type of abrasive blast cleaning process employed can strongly influence the form of localised attack which can occur. More research is required before a detailed account of the mechanisms involved can be given.

4 CONCLUSIONS

Concern that abrasive blasting with glass beads could lead to a loss in fatigue life appears to be unwarranted. Any effects which glass bead blasting or alumina grit blasting may have on the fatigue properties of L93 plate are negligible in comparison to the effect of corrosion. Tests have shown that exposure to alternate immersion in salt solution for 3 days is sufficient to reduce the fatigue strength from 170 to 64 MPa. This may be compared with a reduction of 5 MPa when specimens are alumina grit blasted before testing and a slight increase in fatigue strength of 5 MPa when glass bead blasting is employed. Fatigue tests have further demonstrated that a high percentage of the fatigue strength lost as a result of corrosion may be recovered by removing the corrosion with abrasive blast cleaning. Even with severely corroded material, significant improvements in fatigue strength can be obtained by cleaning the surface with glass beads. The beneficial effects derived from abrasive blast cleaning are thought to arise from a blending out of stress concentrators such as corrosion pits. Compressive stresses introduced by glass bead blasting are believed to play a relatively minor role in inhibiting the initiation of fatigue cracks.

Total immersion tests reveal that the corrosion of L150 aluminium alloy sheet is dependent on the surface preparation. Glass bead blasting reduces the corrosion rate to approximately a third of that of the wet abraded material and restricts the corrosion to the formation of a few large pits. Alumina grit blasting also reduces the corrosion rate, but attack is similar to wet abraded material, the surface being covered with many small pits. Tests on corroded material which was abrasive blast cleaned and then recorroded have shown that provided the precorrosion treatment was not longer than 7 days in 3½% salt solution the pattern of corrosion is repeated. Increasing the initial corrosion treatment to 12 days in 3½% salt solution changes the nature of the attack on glass bead blasted samples from a few large pits to widespread pitting over the whole surface of the test coupon.

The nature of the pitting attack after glass bead blasting is disturbing. In many instances the presence of a single large pit in the surface of a component can be more damaging than when the surface is covered with many shallow pits. The decision to adopt alumina grit blasting in some cases, in preference to glass bead blasting for the removal of corrosion damage on military aircraft, appears to have some justification.

Table 1

FATIGUE STRENGTH (MPa) AT 10^7 CYCLES

	Prior corrosion		
	None	8 hours salt fog	3 days alternate immersion
As machined	170	107	64
Alumina grit blasted	165	150	-
Glass bead blasted	175	160	120

Table 2

PER CENT RECOVERY IN FATIGUE STRENGTH

Prior corrosion	Abrasive blasting	% recovery
8 hours salt fog	Alumina grit	68%
8 hours salt fog	Glass beads	84%
3 days AI	Glass beads	53%

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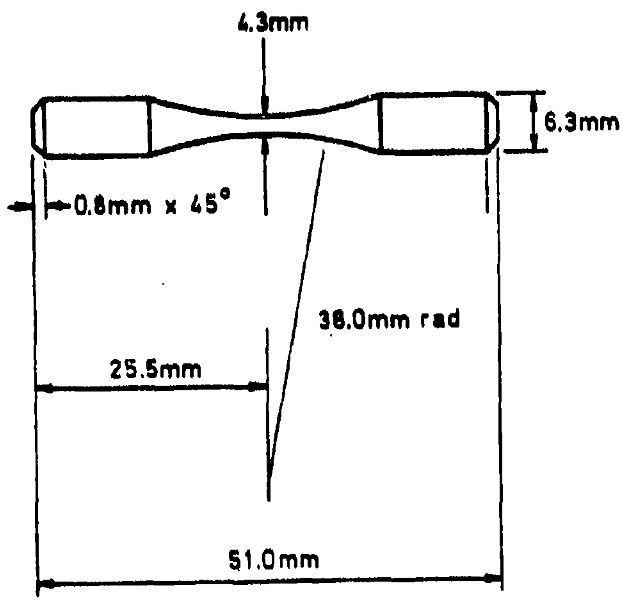

Fig 1 Rotating bending fatigue specimen

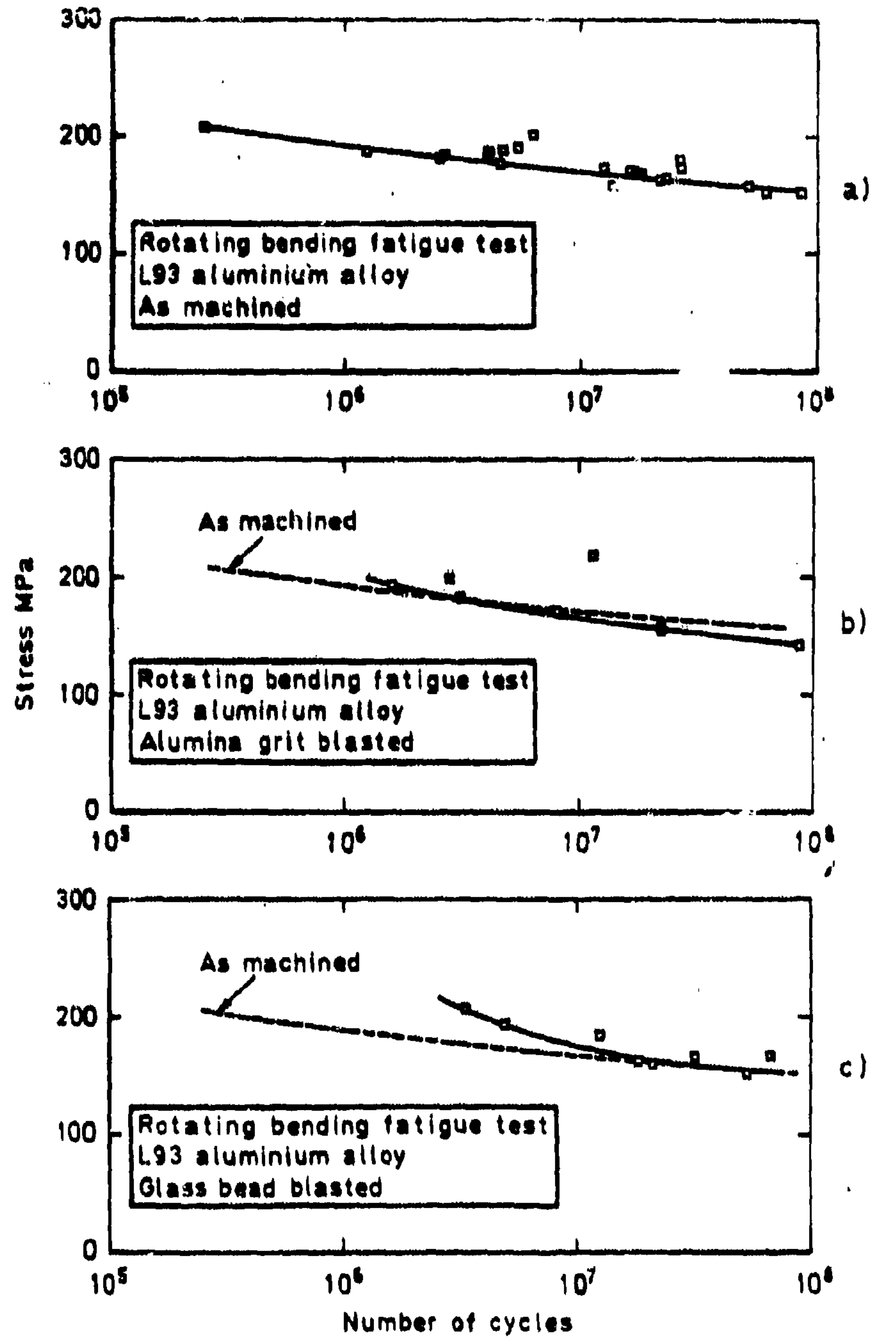

Fig 2a-c Effect of abrasive blasting on the fatigue properties of L93 aluminium alloy plate

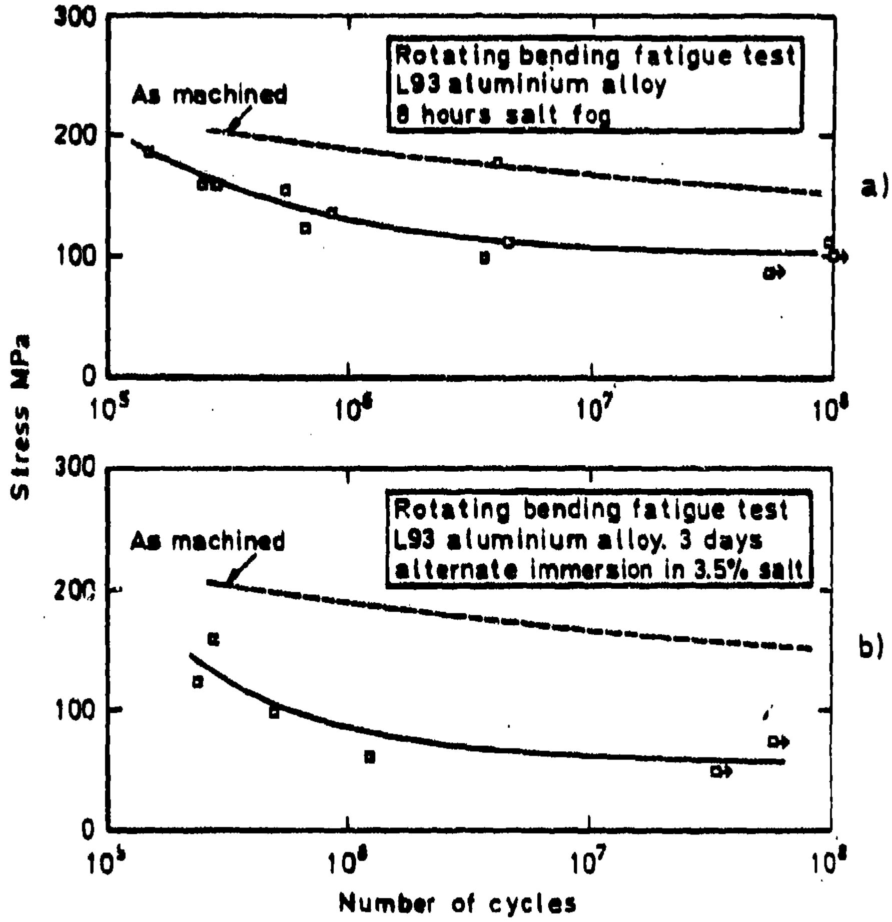

Fig 3a&b Effect of prior corrosion on the fatigue properties of L93 aluminium alloy plate

Fig 4a-6

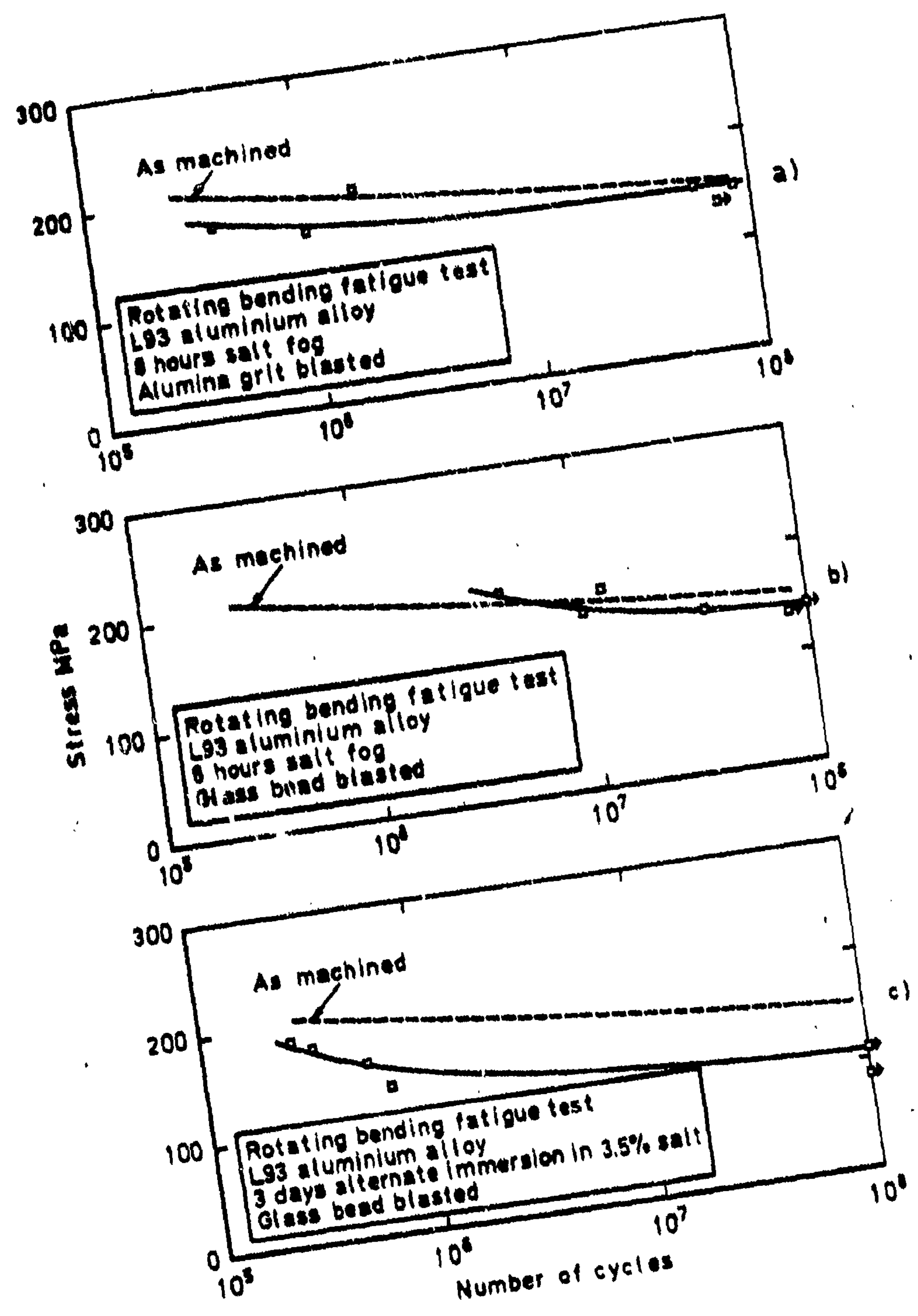

Fig 4a-6 Effect of abrasive blasting on the fatigue properties of prior corroded L93 aluminium alloy

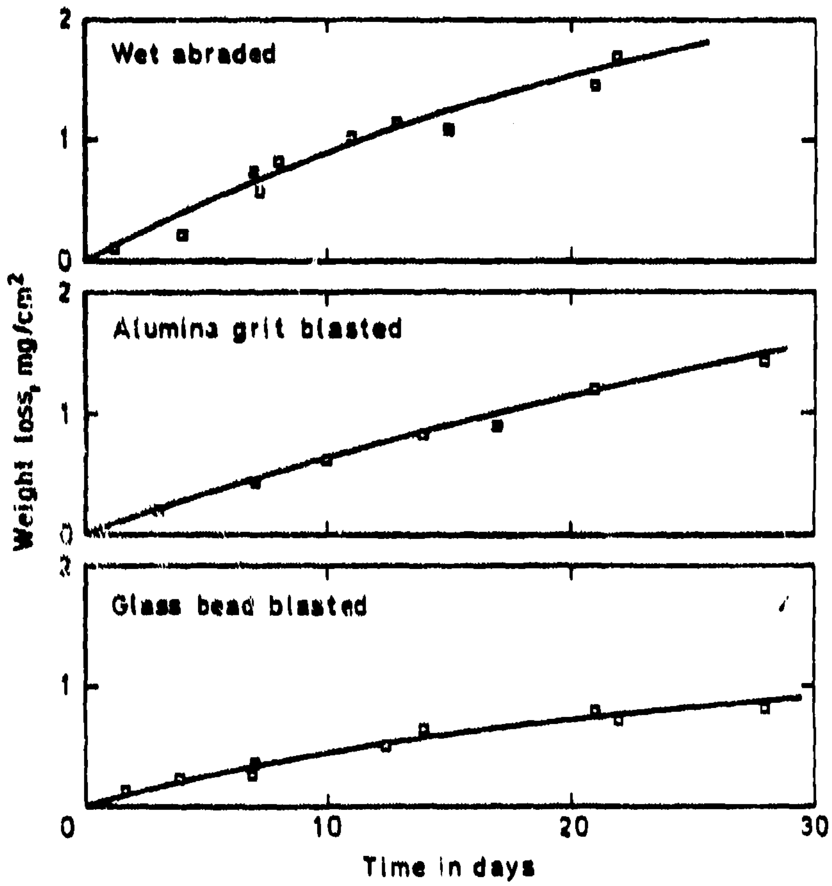

Fig 5 Effect of surface finish on the corrosion of L160 aluminium alloy sheet in 3.5% salt solution

Fig 6

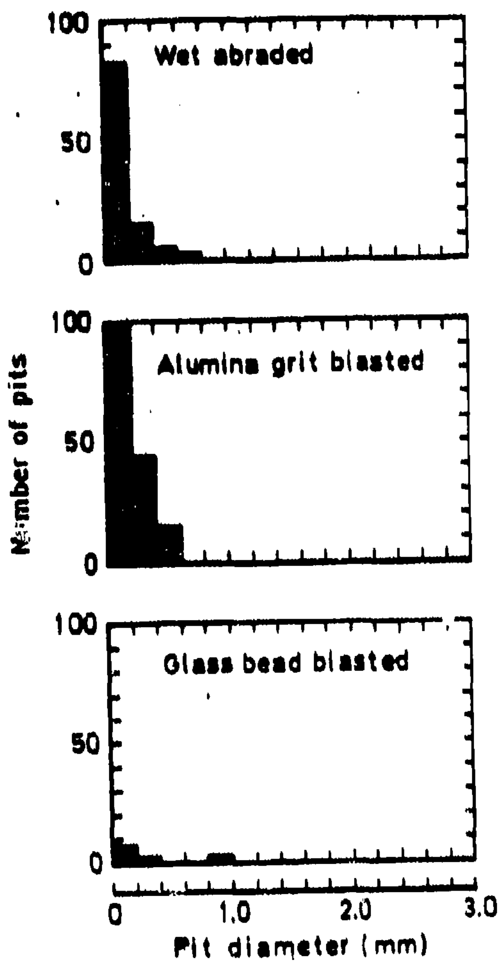

Fig 6 Effect of surface finish on the distribution of pits following 21 days immersion in 3.5% salt solution

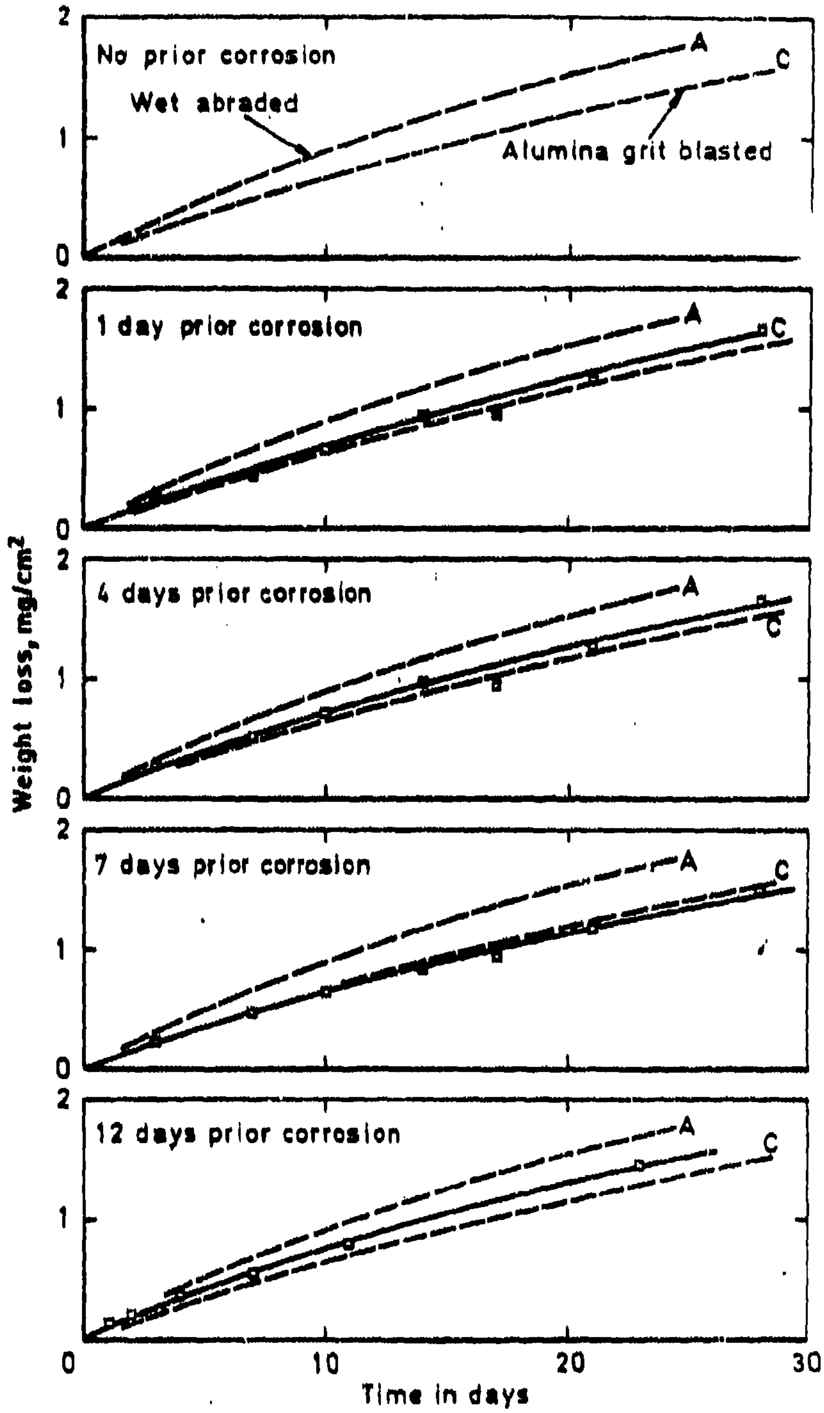

Fig 7 Corrosion behaviour of prior corroded L150 alloy after alumina grit blasting

Fig 8

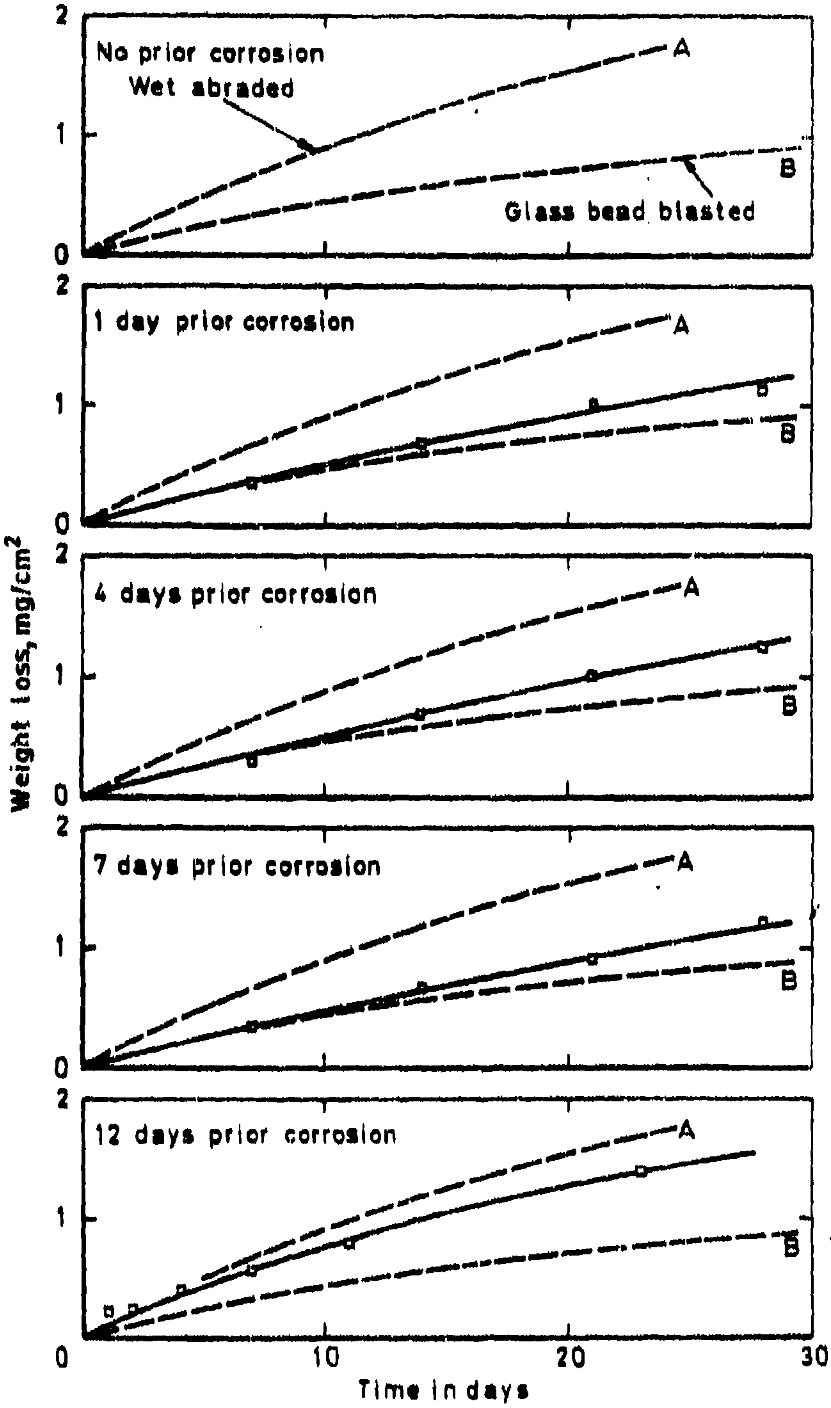

Fig 8 Corrosion behaviour of prior corroded L150 alloy after glass bead blasting

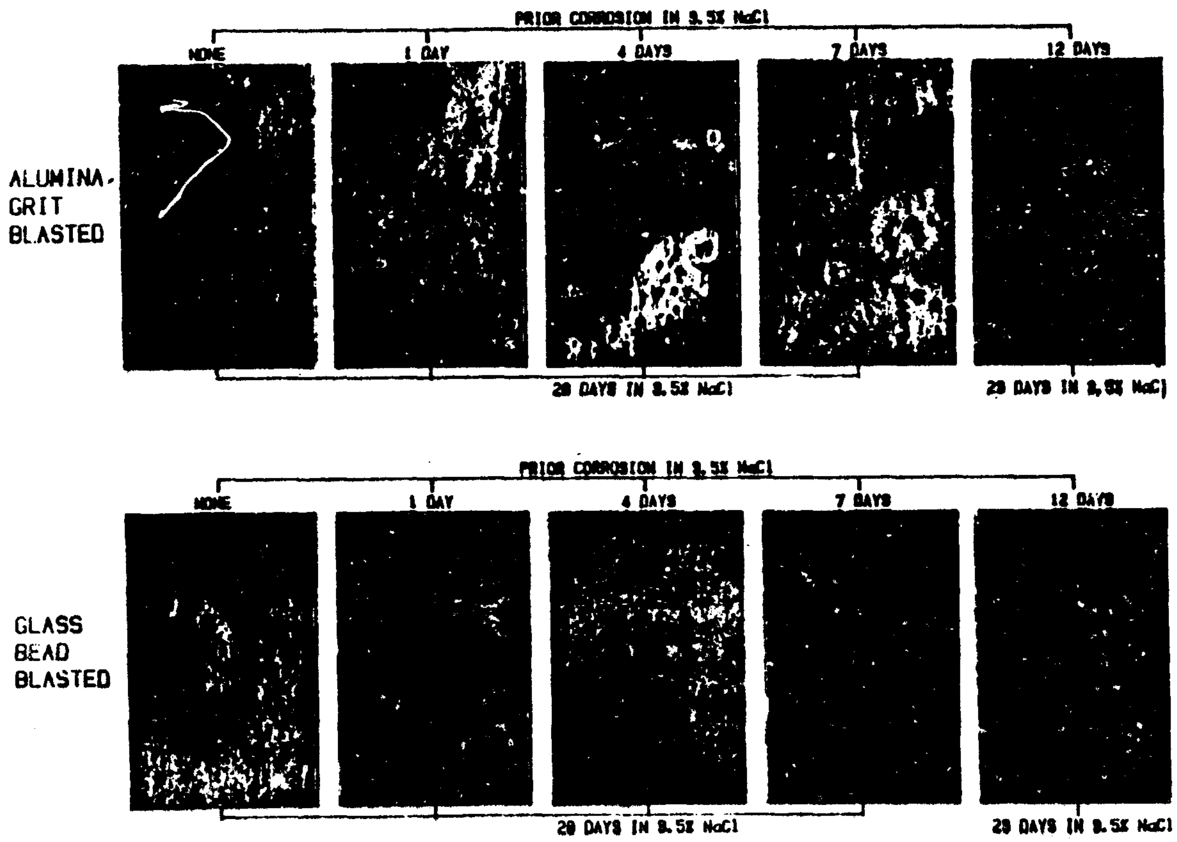

Fig 9 Optical micrographs showing the effect of abrasive blasting on the pitting of L150 aluminium alloy sheet (magnification x2)

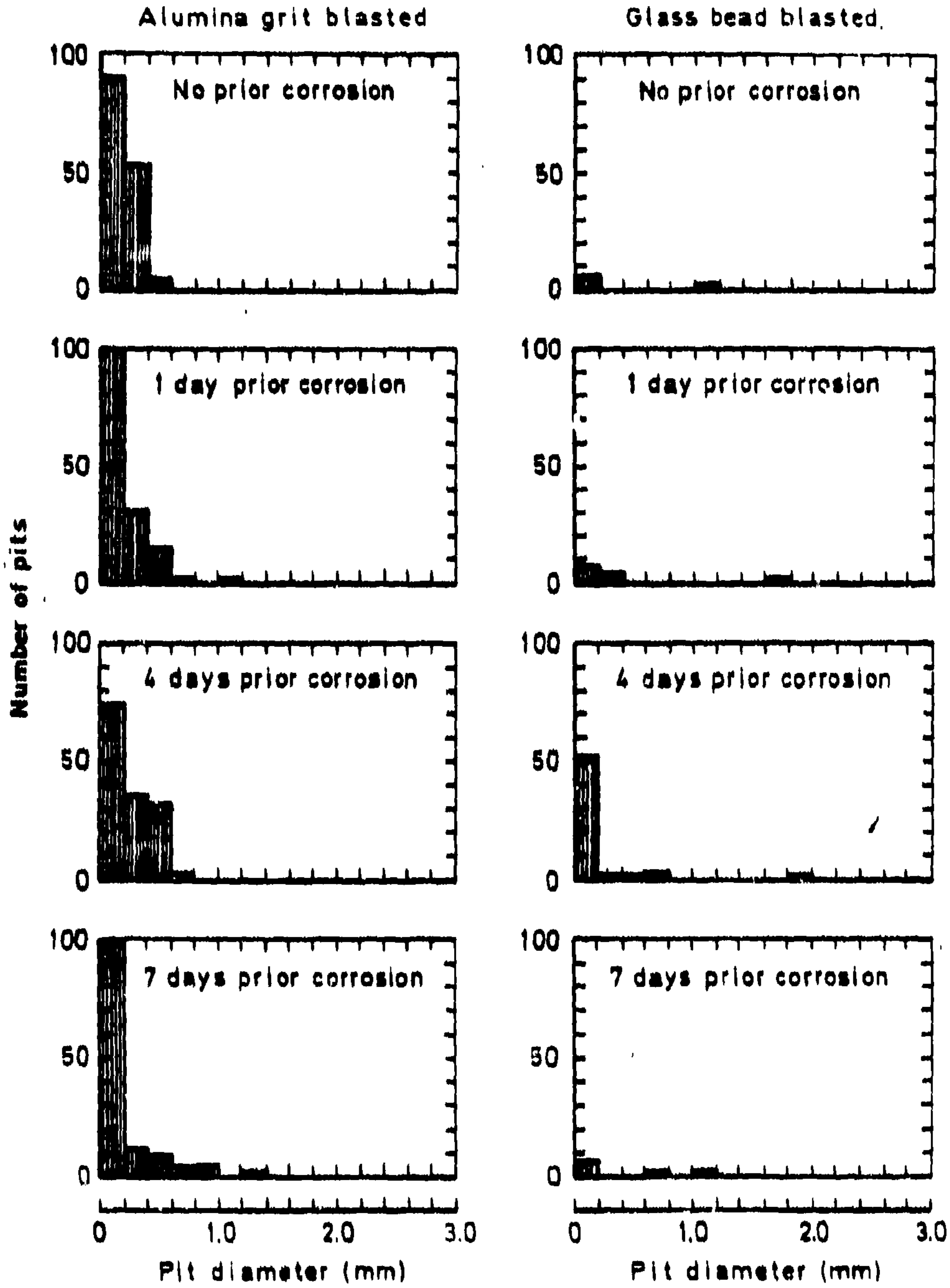

Fig 19 Effect of abrasive blasting and prior corrosion on the distribution of pits following 28 days immersion in 3.5% salt

REPORT DOCUMENTATION PAGE

Overall security classification of this page

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(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Aluminium alloys. Abrasive blasting. Corrosion. Fatigue.

17. Abstract

Rotating bending fatigue tests have established that glass bead and alumina grit blasting have only a slight effect on the fatigue properties of 2014-T6 aluminium alloy. Exposure to salt fog for 8 hours or alternate immersion in 3½% salt solution for 3 days reduces the fatigue strength from 170 MPa to 107 MPa and 64 MPa respectively but substantial improvements in fatigue strength may be achieved by abrasive blast cleaning to remove the corrosion.

Total immersion tests made in 3½% salt solution to examine the effects of abrasive blasting on corrosion have demonstrated that the corrosion rate and type of pitting attack on 2014-T6 aluminium alloy sheet are dependent on the abrasive used and on the amount of corrosion which has occurred prior to blast cleaning.